EXPLOSIVE DESTRUCTION SYSTEM

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ABSTRACT

At the request of the U.S. Army Project Manager for Non-Stockpile Chemical Materiel (PM NSCM), Sandia has developed a transportable Explosive Destruction System (EDS) to treat recovered Chemical Warfare Materiel (CWM). The system is for use on recovered World War I and World War II vintage, explosively configured, chemical munitions that are deemed unsafe for transport or storage. The mission of the EDS is to safely contain the munition blast and fragments, and treat the chemical agent.

The system uses shaped charges to access the chemical agent and destroy the burster followed by chemical treatment of the agent. The entire process takes place inside a sealed pressure vessel. The system can contain up to one pound TNT equivalent of explosive

The system has undergone extensive qualification testing including: non-explosive operational tests with surrogate chemicals and with chlorine; vessel explosive containment tests with a 1.25 pounds TNT equivalent bare charge; open air and in-vessel explosive tests with mock 75 mm artillery, 4.2 inch mortar cartridges, and Livens projectiles; and a complete system test using the shaped charges to open a phosgene lecture bottle followed by chemical treatment of the phosgene. Based on the positive results of these tests, the Army has initiated development of a larger system capable of containing up to three pounds of explosive. In this paper, we review the design, operation, and testing of the system.

INTRODUCTION

The U.S. Department of Defense is required under Public Law 102-484, Section 176 to safely destroy all United States non-stockpile chemical warfare materiel (NSCM). The priority for destroying NSCM has increased because of the Chemical Weapons Convention (CWC) negotiations and the realization that some CWM are in the public domain and others are located close to public areas.

The Army intends to field Munitions Management Device (MMD) systems capable of destroying CWM recovered from small-quantity burial sites. Each MMD system has a specific mission based on the type of CWM located at each site. The MMD systems cover all scenarios for recovered CWM except for munitions that are explosively configured and unsafe for transport or storage. At the request of the U.S. Army Non-Stockpile Chemical Materiel program manager (PMNSCM), Sandia has developed a transportable Explosive Destruction System (EDS) to fill this role.

The mission of the EDS is to destroy explosively configured chemical warfare munitions, contain the blast and fragments in opening the munition, and treat the chemical fill of the munition, without harm or insult to the environment. The EDS is intended for emergency use with World War I and World War II vintage CWM produced prior to 1945. Post WWII munitions have larger bursters that exceed the capacity of the system. Table 1 shows a list of chemical agents that can be treated in the EDS.

OVERVIEW OF EDS

The EDS development program consists of three phases. Phase I was to seek out and select technologies for further development. Together with the Army, we selected a system based on the use of shaped charges to open the munition followed by chemical treatment of the chemical agent. Phase II was to prove out the concept with a sub-scale prototype system. This system is designed to contain up to one pound TNT equivalent total explosive weight. Phase III is the design, fabrication, testing, and documentation of a larger, three-pound EDS. After initial testing of the one-pound EDS prototype, the Army opted to have it upgraded for use with actual recovered munitions. Following this

Symbol	**Common Name**	**Chemical Name**	**Chemical Structure**
BA	Bromacetone	Bromo-2-Propanone	$BrCH_2$-CO-CH_3
CA	Bromobenzylcyanide		Br-C_6H_4-CH_2-CN
CG	Phosgene	Carbonyl dichloride	Cl-CO-Cl
CK	Cyanogen Chloride	Chlorine Cyanide	ClCN
CL	Chlorine	Chlorine	Cl_2
CN	Chloroacetophenone	Chloromethylphenylketone	Cl-CH_2-CO-C_6H_5
CNS	Mixture of CN, PS, and chloroform		
CNB	Mixture of CN, benzene, and carbon tetrachloride		
DA	Diphenylchlorarsine	Diphenylchlorarsine	$(C_6H_5)_2AsCl$
H HS or BB HD; HT	- Mustard - Sulfur mustard - Distilled mustard; 60% mustard, 40% vesicant T	2, 2'-Dichloro-diethyl sulfide	(Cl-CH_2-CH_2)$_2$-S
L	Lewisite	1-Chloro-2-dichloroarsinoethylene	Cl-CH=CH-$AsCl_2$
NC	80% PS, 20% $SnCl_4$		
PD	50% CG, 50% DA		
PG	50% PS, 50% CG		
PS	Chloropicrin	Nitrotrichloromethane	NO_2-CCl_3
GB	Sarin	Isopropyl methylphosphonofluoridate	
VX	Nerve Agent	O-ethyl-S-(2-isopropylaminoethyl) methyl phosphonothiolate	

Table 1: Agents That Can Be Treated In The EDS

upgrade, we began additional qualification tests that are now underway. This paper describes the design and testing of the upgraded one-pound EDS.

The one-pound EDS can handle three common munitions: a 75-mm artillery shell, a 4.2-inch mortar cartridge, and a Livens projectile. The three-pound EDS, now under development will be capable of handling munitions as large as an 8-inch artillery shell.

The operational scenario for the EDS consists of Explosive Ordnance Disposal personnel hand carrying the recovered munition and placing it in the EDS containment vessel. Once the munition is enclosed in the EDS, the shaped charges attack the burster explosive and open the munition, and then the chemicals are added to treat the chemical agent. The treatment process relies on recipes developed by the Army for the various chemical agents. The effluent is treated as a hazardous waste and the system is prepared for the next munition.

The EDS, which is shown graphically in Figure 1, includes the following major components:

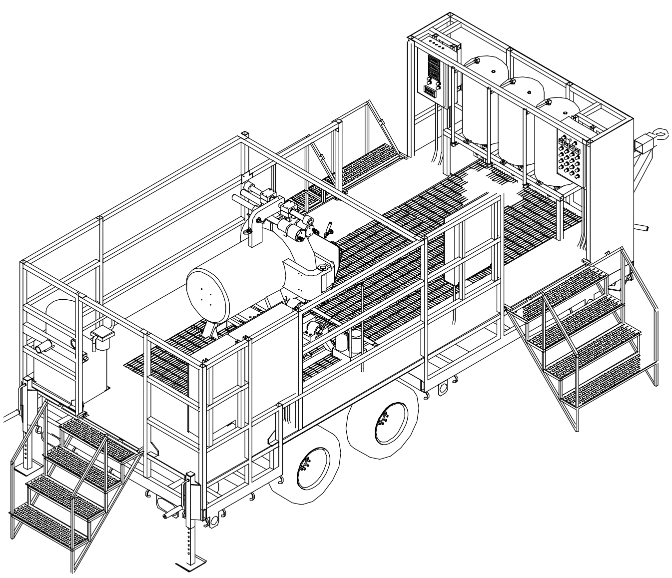


Figure 1: Graphical Depiction of EDS

- The trailer on which the entire system is mounted.
- An explosive containment vessel that contains the blast, fragments, and chemicals.
- A munition opening system that opens the munition with a linear shaped charge and attacks the burster with two conical shaped charges.
- A fragment suppression system that protects the containment vessel from high velocity fragments.
- A firing system that reliably fires the detonators on the shaped charges.
- The chemical storage and feed system that supplies the treatment chemicals to the containment vessel.
- The vessel heater and hydraulic oscillation system to heat and mix the contents of the containment vessel to insure rapid and complete treatment of the chemical agents.

TRAILER

The EDS is mounted on an open flatbed trailer, making the system easily transportable for rapid response in emergency situations. The 8.5 foot by 20 foot, dual-axle trailer weighs about 15,000 pounds and has an 18,000-pound GVW rating. The trailer height is 8 feet.

Figure 2: EDS Ready for Transport

The working surface of the trailer is about a foot above the main trailer structure, or about 37 inches above the ground. The working surface has an open stainless steel grid over a stainless steel secondary containment pan. Stainless steel is used for compatibility with agents and treatment chemicals.

The containment vessel is mounted over the axles of the trailer with the door facing toward the front of the trailer. The chemical supply tanks are at the front of the trailer. The area between these components provides a working area for preparing and loading the munition. All controls and instrumentation displays are readily available from this working area. The electrical supply panels and the hydraulic pump are mounted at the rear of the trailer. Piping and electrical conduit runs under the main deck.

EXPLOSIVE CONTAINMENT VESSEL

The purpose of the vessel is to first contain the explosive shock, fragments, and chemical agent during the munition opening process and then to serve as a process vessel for the subsequent chemical treatment of the agent.

Figure 3: Vessel Mounted on Trailer

The 6.5 ft^3 cylindrical vessel was fabricated from two 316 stainless steel forgings. The inside diameter is 20 inches with 2-inch thick walls. The vessel is designed to contain at least 500 detonations of up to one pound of explosive (TNT equivalent). The hinged door is the same diameter as the vessel, allowing easy access for inserting munitions and removing debris. The door is secured with two large clamps that are fastened with four threaded rods. Figure 4 shows the vessel, door, and clamps.

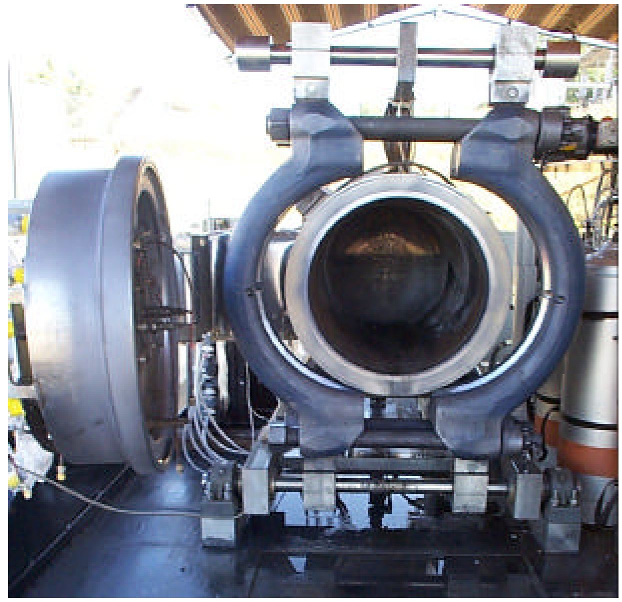


Figure 4: Vessel, Door, and Clamps

The vessel relies on a Grayloc™ all-metal seal, shown in Figure 5, to contain the detonation and the chemical agent. An O-ring provides a backup seal and aids in leak testing. When properly installed, the helium leak rate through the metal seal at 50 psi differential pressure is less than $1x10^{-4}$ std cc/sec.

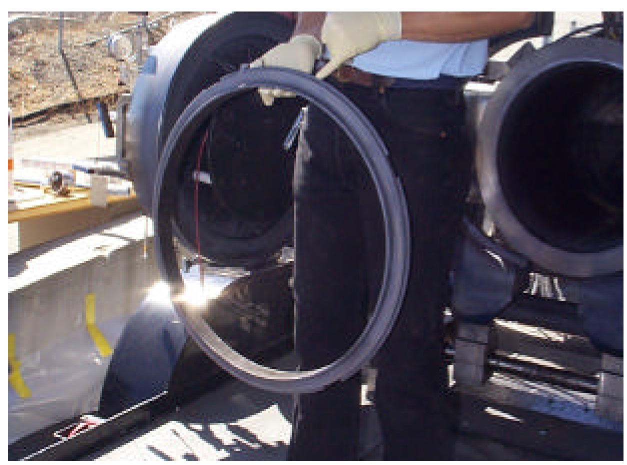


Figure 5: Grayloc All-metal Seal

The vessel includes electrical feed-throughs for the high-voltage exploding bridge wire (EBW) detonators. Ports for adding and draining fluids use high-temperature valves with metal-to-metal seals. Figures 6 shows the inside of the door. Near the center are two spray nozzles for injecting the treatment chemicals. At the bottom are drains with sieves for removing effluent. There are four electrical feed-throughs with terminal connectors.

Figure 6: Feed-throughs On Inside of Door

We performed computer simulations of the vessel response to the detonation of a 1.25 pound, centrally located explosive. We used the Eulerian wave code, CTH, to simulate the explosion and calculate pressures on the interior surface of the vessel. These pressures were then transferred to the Lagrangian code, DYNA2D, to predict the structural response of the vessel. The calculations showed no yielding of the vessel. The general conclusions from the analysis were:

- The predicted peak pressure in the vessel is 19,000 psi.
- The maximum predicted stress of 21,000 psi occurs on the inner surface near the waist of the vessel.
- The maximum predicted stress on the outer surface is 16,000 psi.
- The maximum predicted strain on the outer surface is 560 microstrain (hoop direction).
- The yield strength of the vessel is about 2.5 times the peak predicted stress with one pound of TNT.

We also performed a vessel life analysis using principles of fracture mechanics. From this we determined that 500 detonations is a conservative estimate of vessel life. The actual vessel life will likely be limited by other factors, such as wear on the vessel sealing surface.

ACCESSING MUNITIONS WITH SHAPED CHARGES

Once the munition has been recovered and placed in the EDS vessel, the contents of the munition must be exposed and the burster destroyed before the chemicals can be treated. These requirements are accomplished with a combination of linear and conical shaped charges. The use of shaped charges is a simple, safe, repeatable, and understood practice. Shaped charges were chosen over mechanical, chemical and thermal mechanisms because they require minimal access through the containment vessel wall, they are exceptionally reliable, and their design is well characterized.

A single pre-formed length of copper linear shaped charge (LSC) is used to open the main body of the munition and expose the contents for treatment. The LSC is attached to the lower half of the fragment suppression system for ease of assembly and to maintain the correct standoff distance for an optimum cut. Experiments with the three munitions of interest have demonstrated that the LSC makes a complete cut in the munition, separating it into two pieces and fully exposing the chemicals within. Detonators are connected to the LSC at each end for increased reliability.

Two copper conical shaped charges (CSC) are used to break open the burster charge canister in the munition and detonate the burster explosives. The CSCs are positioned onto the upper half of the fragment suppression system above the case of the target munition providing a pre-determined standoff distance. The CSCs are fired in the direction of the burster at the same time as the LSC is fired.

Figure 7 shows pieces of two 4.2-inch mortar cartridges after exposure to the shaped charges. The munition on the right did not have a burster charge. The LSC sliced a single segment from the top of the munition. The jets from the CSCs penetrated all the way through the shell and into the solid block that was below it. The block has been cut to show the depth of penetration.

Figure 7: Opened Munitions With and Without Burster Charge

The CSC design was chosen to exceed the criteria for reliable detonation of the burster explosives by shaped charge impact. The burster explosives will likely be Tetryl, TNT, or a combination of both. However, it is not known whether the TNT is cast or pressed, nor is it known to what density the material was manufactured. Also, the condition of the explosives is in question. The effects of aging may be pronounced. The explosives may be chemically contaminated by the agent inside the munition, or at least soaked by the agent, changing its detonation properties. All of these issues lead to uncertainty as to the detonation sensitivity of the burster explosives. However, the burster explosives do not need to be completely destroyed in the CSC attack, as the treatment process will destroy residual explosives with the chemical agent as long as the burster well is penetrated.

The CSC is a 40-gram, Composition A-3, multi-tapered copper CSC designed by Tracor Aerospace. This CSC was selected because it meets the initiation requirements of TNT and the need for precision and repeatability.

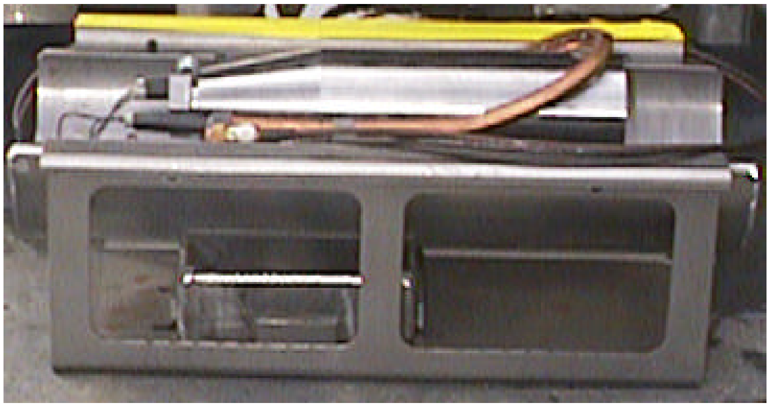
For safety, exploding bridge-wire detonators are used to initiate the shaped charges. These detonators are very insensitive to unexpected or undesirable energy inputs (static, impact, etc.). A high-energy firing system is required to initiate these detonators.

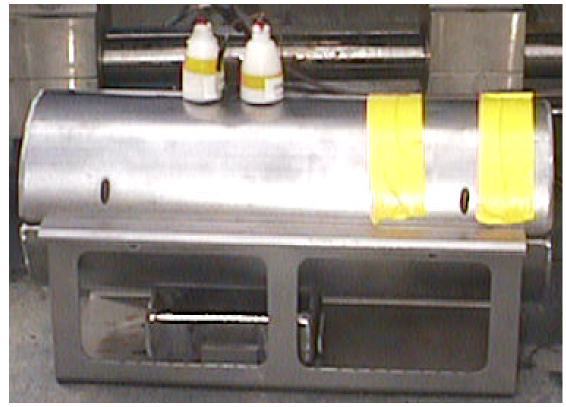
FRAGMENT SUPPRESSION SYSTEM

A fragment suppression system is necessary to mitigate high velocity fragments that could damage the interior of the EDS vessel during operations. Fragments will come from the LSC, and CSCs, the burster charge case and the case of the munition itself.

The core of the fragment suppression system is a steel cylinder separated lengthwise into two sections. The cylinder is connected to a cradle that supports the system inside the EDS vessel. A three-sided steel support is positioned inside the lower half of the cylinder to hold the munition and to provide shock absorption below the munition. A steel block is positioned between the lower half cylinder and the cradle bottom to stop the CSC jet in case of complete penetration. Figures 8 and 9 show the assembly for a 75 mm munition.

In practice, the LSC and CSCs are attached to the lower and upper halves of the fragment suppression system before the recovered round is placed in the system. The detonators are attached to the charges and cables are connected to the detonators, strain relieved, and electrically shorted for safety. The munition will be





Figures 8 and 9: A SETH 75 mm munition in the lower half of the fragment suppression system with the LSC in place and the top view of the assembled system.

positioned in the pre-assembled bottom half of the fragment suppression system. The pre-assembled upper half of the fragment system will be placed on top to complete the system, and the entire unit will be positioned inside the EDS vessel (Figures 10). The final fire system connections will be made, and the vessel door will be closed, strain relieved, and then electrically shorted until the unit is fired.

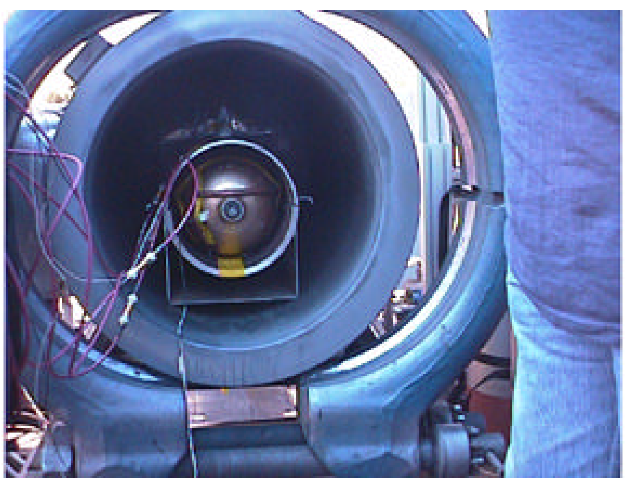


Figure 10: A SETH Livens Projectile With Fragment Suppression System Inside Vessel.

FIRING SYSTEM AND DETONATORS

The firing system initiates the LSC opening charge and the CSC burster charges. The firing system is a high-voltage capacitor discharge unit (CDU) capable of reliably firing four detonators (1.5 x 40 mil exploding bridge-wire) over cable lengths of up to 50 ft. The fire system is modular so that parts can be tested and replaced easily. Two systems have been designed using different components to increase the probability of being able to obtain major, hard-to-find components. The operating parameters of the two systems are identical.

The firing system consists of a CDU, a high-voltage trigger module, a high-voltage power supply, a control module, monitoring and diagnostics equipment, and safety controls. The entire system can be operated from an easily accessible panel (Figure 11). A redundant system is mounted in the same panel.

The CDU consists of a 1-micro-Farad (μF), 3-kV capacitor triggered from a 150-V trigger module. A high-voltage power supply transforms 24 V DC to 3000 V and 150 V for the power to the CDU and trigger module respectively. A control module makes the connection from the power, arm and trigger signals to the appropriate modules.

An LED meter mounted in the fire system panel monitors the CDU charge voltage. BITE indicators monitor the outputs from the CDU and the trigger module. These indicators must be manually re-set after each firing. Also located on the fire system panel are shorting connectors for the detonator cables and continuity meters for detonator connection checks. A high potential (HiPot) breakdown tester is mounted on the panel to enable testing of the cables and feed-through connectors associated with the firing system.

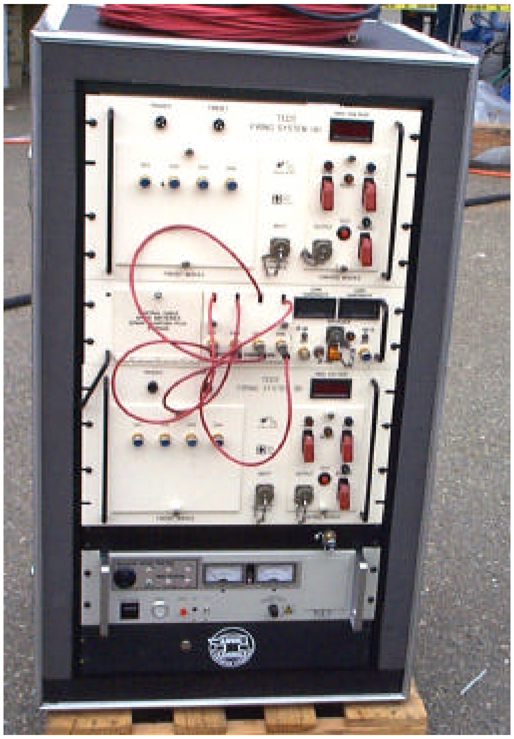


Figure 11: Firing System Control Panel

An operator can remove the entire fire system from the EDS vessel by using the 50-ft detonator cables. Also, the operator can remove the control module an additional 200 ft from the fire system panel for operation.

CHEMICAL TREATMENT SYSTEM

Any destruction system for CWM requires that the agent and energetics be converted to waste that can be safely transported. EDS uses a low-pressure and low-temperature chemical treatment method to transform chemical agents to less toxic species. The process, which is sometimes called neutralization, relies on recipes developed by the Army. The end products of treatment reactions are mixtures of aqueous and/or combustible organic species that can be transported as commercial hazardous waste.

Figure 12: Chemical Supply Tanks

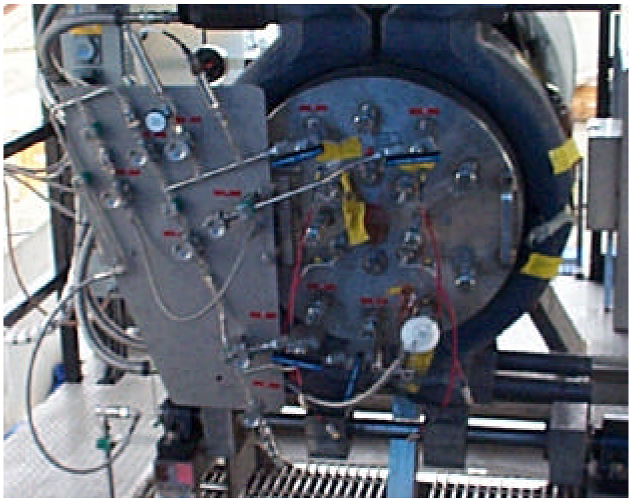


Figure 13: Sample Manifold and Vessel Door

The treatment is done inside the containment vessel after the munition is opened so there is no transfer of untreated chemical agent. Treatment chemicals and water are stored in three, 25-gallon, stainless steel tanks (Figure 12). The tanks are heated to make the viscous fluids easier to pump and to speed up the treatment process. The fluids are pumped into the containment vessel through a spray nozzle. A valve manifold on the vessel door (Figure 13) allows the operator to control the transfer of chemicals, collect samples to confirm that the treatment is complete, and drain the liquid effluent. Gaseous effluent is vented through a silica gel/ASZM-TEDA carbon filter.

Three treatment chemicals will be used for EDS. They are mono-ethanolamine (MEA), aqueous hydroxide, and aqueous bisulfite (and their combinations). We combined the different agents into groups of chemicals having similar reactivities (see Table 1.) The organics and organoarsenics groups will be treated using MEA alone or in combination with aqueous hydroxide. Arsenic is a special hazard because of its persistent toxicity even after total treatment of the original chemical agent. The organics often yield multiple species upon basic hydrolysis or aminolysis. These materials may be hazardous wastes, but will not have the handling and transportation restrictions associated with the highly toxic starting materials. The chloride group will be treated with aqueous hydroxide. Chlorine will be treated by aqueous bisulfite. This reaction is spontaneous and limited only by the solubility of chlorine gas in the aqueous phase. In the absence of dissolved metals, the products of bisulfite treatment are non-hazardous.

We have verified destruction in our laboratories of those agents that can be purchased as industrial chemicals. Studies with the other agents have been performed by others for the NSCM projects and we will use these data as well as historical data.

All of the treatment reactions are exothermic. Some reactions (such as phosgene or chloroform with hydroxide) generate sufficient energy to be a concern in a batch process. However, in the EDS with the large thermal mass of the thick-walled vessel, the heat of the reaction will only aid in warming the vessel and will not create dangerous overpressures.

Besides the chemical agents, any residual explosives must be treated. The shaped charges are designed with a dedicated conical shaped-charge to pierce the burster at the same time as they open the shell. This yields an extremely high probability of detonating the burster charge. Unfortunately, there is never a complete guarantee that the explosives will detonate because these munitions may have been buried for more than 50 years in uncontrolled conditions and may have undergone dramatic chemical and physical degradation. We anticipate that the shaped-charge will detonate, or at least ignite, the explosives. Traces of unreacted explosives (likely TNT or Tetryl) may remain after the initial detonation.

We performed experiments in which solutions of TNT or Tetryl and individual chemical agents were exposed to MEA. The MEA (used in excess) always treated the explosive as well as

Table 2: Agent Groupings

Agent Group	**Individual Agents**
Organics	acrolein, bromoacetone (BA), bromobutanone (bromessigester), bromobenzyl cyanide (CA), chloroacetone, chloroacetophenone (CN), mustards (H, HD, HS, HT), chloroacetophenone/chloropicrin/chloroform (CNS), dichloroethylthiodiethylether (Vesicant T).
Chloride Family	phosgene (CG), chloropicrin (PS), $SnCl_4$/PS (NC), $SnCl_4$, $TiCl_4$ (FM), chloropicrin/phosgene (PG), cyanogen chloride (CK).
Organo-arsenics	lewisite (L), phosgene/diphenylchloroarsine (PD), diphenylchloroarsine (DA).
Oxidizer	chlorine (Cl_2)

the chemical agent within one hour at 40 °C. These experiments are prejudiced towards rapid reaction because all the reaction occurs in solution. Actual reaction inside EDS would be slower because solubility limits the reaction rate. Aqueous hydroxide efficiently destroys nitrated aromatics only if the particles are small and the reaction is agitated. Treatment of explosives in the EDS system is meant only to clean up traces of explosives, not as a method of bulk explosive destruction.

HEATING AND OSCILLATION SYSTEM

The speed of treatment is limited by the solubility of the material in the treatment medium. If the agent has polymerized or degraded, the treatment may take longer. Inorganic chlorides may yield voluminous precipitates of oxides/hydroxides under these conditions, so agitation and excess treatment chemicals are required. In the EDS system, the chemicals are heated to near the boiling point and agitated, accelerating the reactions.

Since any hardware inside the vessel must withstand the explosive blast, we opted to both heat and agitate the vessel externally. The vessel is heated with ten 1-kW band heaters using a feedback control system. It takes 3 to 4 hours to heat the contained fluids to 100°C. Fluid temperature can be controlled within ± 4°C. The treatment chemicals are heated to about 40°C before they are injected into the vessel.

The vessel is mounted on pillowblock bearings allowing it to tilt forward and backward. A hydraulic system is used to oscillate the vessel between ± 40 degrees from the horizontal position. The entire stroke through 80 degrees takes about 9 seconds. The vessel can be stopped in any position to aid in draining or sample collection.

SYSTEM TEST RESULTS AND PLANS

We conducted a series of tests to qualify and demonstrate the one-pound EDS system as initially configured. Initial tests evaluated the chemistry, heating, chemical feed, and vessel agitation. The second set evaluated explosive containment.

In the first treatment test, we treated methyl salicylate (oil of wintergreen or OOW) with MEA and NaOH. OOW has been used by the army as a surrogate agent. It was useful in this test because it reacts with both the MEA and NaOH treatment chemicals to form two different products. All aspects of the system worked as expected. The effluent was analyzed using both LCMS and NMR. The concentration of OOW was below the detection limit of 20 ppm.

In the second test we treated one pound of chlorine with sodium bisulfite. Chlorine is one of the agents that EDS is designed to destroy. The chlorine was generated inside the EDS vessel using a reaction of calcium hypochlorite and methane sulfonic acid. Again the system worked as expected and the concentration of chlorine in the effluent was below the detection limit.

The initial explosive containment tests used bare charges of C4 explosive. Figure 14 shows a charge and detonator assembled in the vessel. The first test used 170 grams of C4 (200 grams TNT equivalent), which matches the combined explosive load from the burster and the shaped charges for a 75-mm artillery test.

This was followed by a 25% overtest with 474 grams of C4 (1.25 pounds of TNT equivalent) to qualify the vessel for repeated use with one pound TNT equivalent. The tests were successful. Helium leak measurements before and after the detonations showed no change in the leak rate.

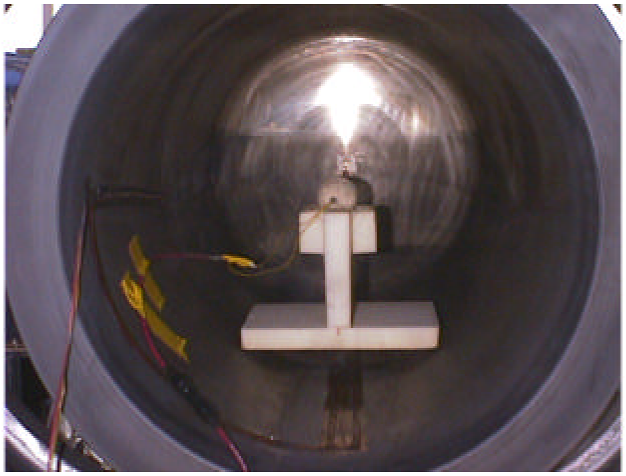


Figure 14: Bare Explosive Charge in Vessel

Strain gages on the vessel wall showed reasonable agreement with the computer model described earlier. Strain data from one location on the vessel wall are shown in Figure 15.

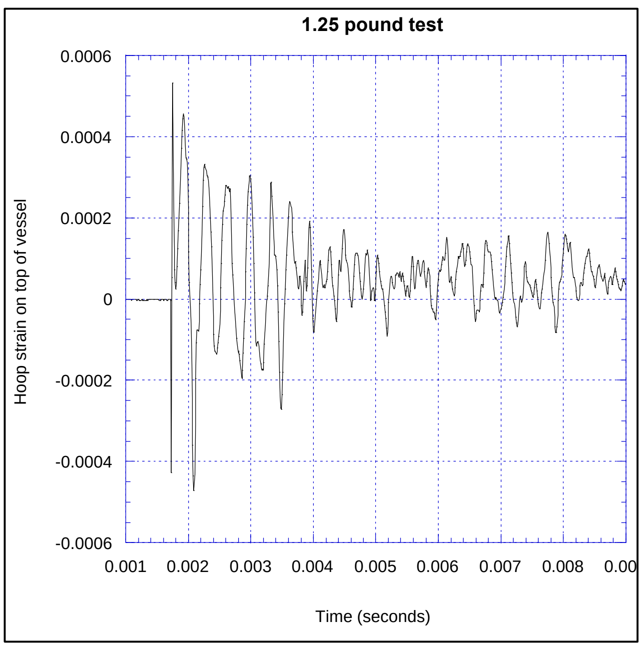


Figure 15: Typical Strain Data

The shaped charges and fragment suppression system were then demonstrated on a series of tests with each of the three munition types. The special evaluation test hardware (SETH) munitions on some of these tests were filled with borate to provide a non-hazardous surrogate for the chemical fill. The borate was neutralized with vinegar. The fragment suppression system worked as designed. Visual inspection revealed no damage to the vessel other than superficial scratches.

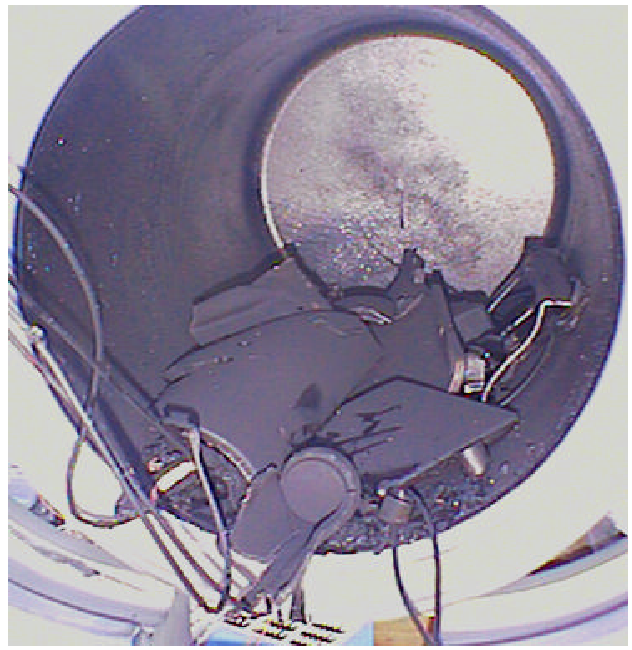


Figure 16: Inside of vessel after test with 75-mm artillery round.

Figure 17: Sorted Pieces of the Munition and Fragments Suppression System.

Figure 16 shows the interior of the vessel after a test with a 75 mm round (no surrogate agent). Figure 17 shows the sorted pieces. The munition fragments are at the top of the picture. Pieces of the fragment suppression cylinder are at the left and the cradle is in the lower right. The cluster of small fragments in the lower center is from the burster.

As a final test of the entire system, we conducted a test with phosgene. The objective was to demonstrate the functionality of the chemical treatment system in concert with the explosive opening/firing system and the chemical sampling system on a combined chemical and explosive hazard. This test was the closest replica to the actual field use of the EDS and exercised all aspects of the system. A commercial lecture bottle containing one pound of phosgene gas was ruptured with linear shaped charges and the contents were treated with aqueous hydroxide. The phosgene bottle with the fragment suppression system inside the EDS vessel is shown in Figure 18.

The system worked well during all of these tests, although several options for improving the safety and performance were identified. Minor improvements were made continuously throughout the testing program. More significant changes were made during the system upgrade after the initial testing program. These included changes to the chemical supply and sampling manifold and increased motion in the vessel oscillation system. After these changes, a second qualification test program was begun. These tests, which were underway at the time this paper was written, include repeats of the tests described above. Testing is scheduled to be completed in mid April 1999. The system will then be delivered to the Army.

CONCLUSION

The one-pound Explosive destruction System provides the capability to dispose of recovered, explosively configured, chemical munitions in a safe manner. The explosive containment capability of the vessel was demonstrated through computer modeling and through a 1.25 pound bare charge overtest. The containment capability was further demonstrated along with the munition opening system in a series of SETH munition tests with 75-mm artillery shells, 4.2-inch mortar cartridges, and Livens projectiles. Tests with phosgene, chlorine, and various surrogate chemicals have demonstrated the treatment, sampling, draining, and rinsing capabilities of the EDS. The system will be delivered to the Army in April 1999. Development of a three-pound system is underway.

Figure 18: Phosgene Cylinder and Fragment Suppression System In Vessel

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